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Technical Notes & Surgical Techniques

Some technical nuances for deep brain stimulator implantation

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ABSTRACT

Protocols for deep brain stimulator (DBS) implantation vary significantly among movement disorders centers despite the need to address similar operative problems. The general steps of this procedure are well accepted, but there are many seemingly minor, yet important nuances not extensively discussed in published descriptions. A classification and the details of the nuances adopted by a single institution may therefore be helpful in providing a basis for discussion and comparison. We describe operative nuances adopted at the Georgia Regents Medical Center (GRMC) for DBS implantation that may not be universally employed. The problems of DBS implantation considered here include stereotactic planning, draping, creation and use of the burhole, physiological testing, anchoring of the electrode, financial considerations, and overall technique. Fourteen categories of operative nuances were identified and described in detail. These include the use of specific anatomical relationships for planning, the use of clear and watertight drapes, countersinking of the burhole, the use of gelfoam and tissue glue to seal the burhole, methods to review the entire microelectrode data simultaneously, blinded communication with the patient during macrostimulation, fluoroscopic marking, MRI compatible protection of the electrode tip, financial considerations effecting choice of operative materials, and restriction to a single operator. The majority of these have not been extensively described but may be in use at other centers. The many operative problems arising during DBS implantation can be addressed with specific technical nuances.

Introduction

Although there is consensus for the general requirements for DBS implantation such as the need for imaging, there are little Class I data to support any particular approach [1]. Accordingly, the operative details for this procedure vary between centers depending on the specific local surgical philosophies and opinions. Several centers have published excellent reviews of the operative techniques they have chosen [2–4], many of which have been adopted by others. In addition to these techniques, however, procedures as complex as DBS implantation also contain many steps that seem minor but that are essential for success. Such nuances often escape the general published descriptions, are often not universally adopted, and are not described by any systematic method for their classification. Believing that a description of the local practices of a single institution can be helpful in guiding discussion and comparison of the various surgical options, our goal in this work is to classify and describe some minor nuances of DBS implantation that have been helpful at our institution.

We describe these nuances without giving Class I data to justify their use for two reasons. First, many would be difficult to study in this fashion. For example, the method of draping with clear plastic sheets is widely used and is thought to improve communication between surgeon and anesthesiologist and patient, minimize patient claustrophobia, and (as we comment later) may have financial implications for the DBS program. However, choosing meaningful endpoints for a randomized, controlled trial of draping has inherent problems that may be prohibitive. The second reason we do not offer Class I evidence for each of the chosen nuances is that our goal is to describe a complete collection of minor methods that we have found helpful for DBS implantation. Including Class I data to justify each of these many techniques is well beyond the scope of a single article.

We do not claim that our protocols are the only way to address the operative problems of DBS implantation, nor do we claim that our methods are superior to others. Instead, we wish to convey our sense of the craft of this procedure rather than its science. Our hope is that an aggregate description of these small but important nuances may be helpful by drawing attention to the many problems inherent to DBS, suggesting a method for their classification, and suggesting a few possible approaches to their solution.

Operative techniques

Our nuances are grouped into the following categories: stereotactic planning, draping, burhole issues, physiological testing, electrode anchoring, financial considerations, and overall technique.

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Stereotactic planning

Nuance 1: stereotactic planning

No single method for localization is perfectly accurate [1,5–7], and so we apply each method in a 'round-robin' fashion, modifying the target and trajectory at each step and repeating iteratively until the resulting trajectory best satisfies all of the requirements.

Subthalamic target. As is commonly done, we first align an inversion recovery MRI sequence obtained with a stereotactic frame in place to the AC–PC plane. This sequence is then used as the reference to merge with all other available sequences (including a preoperative 3 T MRI in the axial and sagittal planes, a CUBE FLAIR sequence reconstructed in all three planes, and the 1.5 T MRI inversion recovery sequences in the sagittal plane obtained on the day of surgery) so that the coordinates it carries are not altered. All sequences are merged to avoid errors later in the procedure. We then cycle through our criteria for subthalamic nucleus (STN) targeting listed in Table 1.

The modified axial slice most likely to contain our target is identified, usually as the first slice superior to the optic tract containing parts of the AC, mamillothalamic tract (MMT), and the red nucleus (see Table 1). As others have done [2,5,6,8,9], we use the anterior border of the red nucleus and the MMT as landmarks for the mid-segment and anterior border of the STN, respectively (Fig. 1). Forel's field H2 lies as a hyperdensity adjacent to the MMT, and should not be confused with the anterior pole of the STN. We then choose a target based on these criteria. A distance of the target to the midline of less than 11 mm or greater than 13 mm is cause to proceed with great caution.

The sagittal anatomy is then reviewed using direct sagittal acquisitions and sagittal reconstructions. The STN is often directly visualized as a hyperdense structure in these images, as is the thin, hypodense zona incerta marking the roof of the STN [10]. Furthermore, because the STN lies within the angle formed by the descending internal capsule and the hypodense substantia nigra (SN), visualization of these two structures yields another clue for STN localization. In addition, the SN serves to locate the STN floor and guides our superior–inferior coordinate. Choosing the sagittal slice showing the greatest amount of STN, we place the target approximately 2 mm anterior to the midpoint of the STN at the superior boundary of the SN. A more posterior site may be too close to the adjacent internal capsule because the posterior STN is very narrow.

We then review the 'probe view' that displays the entire trajectory as a colored line in one oblique plane, and the intersection of the trajectory as a colored dot superimposed upon the perpendicular plane. The appearance of this dot within the SN confirms that the trajectory passes through the STN floor, and the appearance of the dot within the STN using the inversion recovery sequences (which is often well seen as a linear hypodense structure in these oblique images) confirms targeting.

We also use images of the stereotactic atlas that are loaded within our planning software, deforming them in perpendicular directions to best match the MRI images. Because the putamen and globus pallidus are usually easy to identify, deformations are made to match these structures to the atlas. The deformation software is limited, however, and it can be difficult to obtain a close match between the atlas and the MRI image. We have found it helpful to import the contours of the atlas together with the MRI image into image software (Photoshop, Adobe, San Jose, CA). The 'warp' option allows portions of the image to be deformed separately, so that a precise match of landmark structures such as the fornices, the MMT, red nucleus, putamen and globus pallidus is possible (Fig. 3).

The FLAIR sequences reconstructed from the CUBE acquisition usually clearly demonstrate the combined signal of the STN and SN, thus providing further confirmation of the target position.

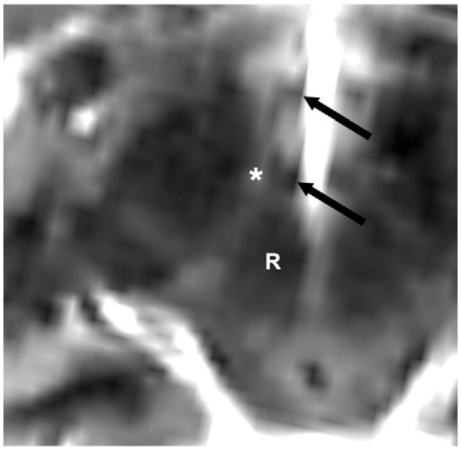

Fig. 1. Axial inversion recovery MRI image showing fornix (upper arrow), mamillothalamic tract (lower arrow), the area of H2 and the ansa lenticularis (*) and the red nucleus (R).

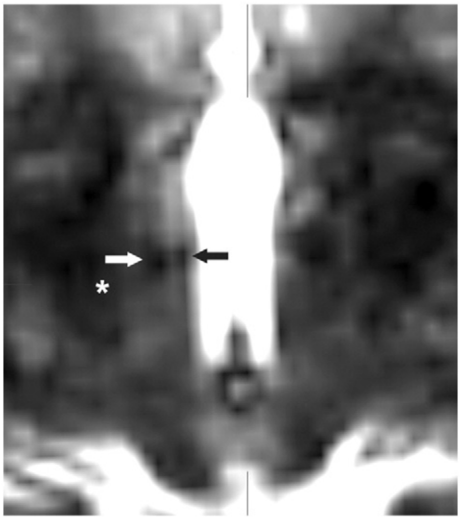

Fig. 2. Axial inversion recovery MRI image showing mamillothalamic tract (black arrow), H2 (white arrow) and region of VIM (*). The contralateral mamillothalamic tract and H2 can be seen but not distinguished from each other.

Table 1
Criteria for localization of subthalamic nucleus (STN).

3 T MRI sequences fused to operative 1.5 T sequences
Orient dataset to AC–PC plane
Use vertical axis of 3rd ventricle rather than interhemispheric plane for orientation
Start with slice containing parts of anterior commissure, mamillothalamic tract and red nucleus (corresponding to Hv-3.5 or Hv-4.5 on Plates 54 or 55 of SWA[a])
Anterior border of red nucleus marks midpoint of STN
Mammillothalamic tract marks anterior border of STN
Distance to midline should be approximately 12 mm
Forel's H2 should not be mistaken for anterior STN
STN lies within angle formed by internal capsule and substantia nigra on sagittal slice, and inferior to zona incerta
Target should be at midline of STN on sagittal slice (not posterior)
Target should be just superior to substantia nigra on sagittal slice and probe view
Target should be within hypodense STN seen on probe view
Use of resident Schaltenbrand–Wharen atlas
Symmetry to contralateral side if prior electrode has been placed

[a] SWA = Schaltenbrand–Wharen atlas [8].

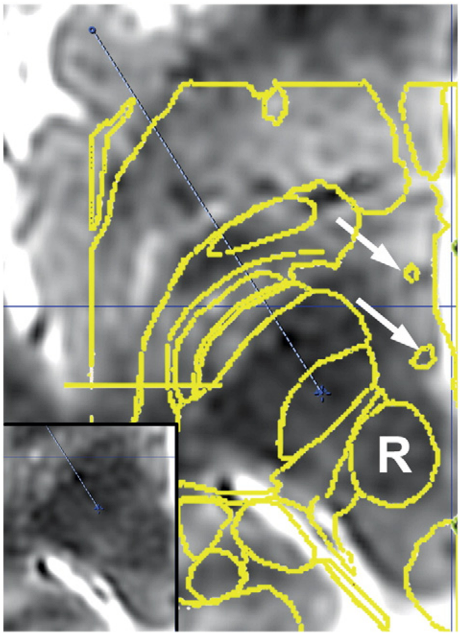

Fig. 3. SWA template superimposed upon an axial MRI slice. The template has been 'warped' so that the outline of the fornix, mamillothalamic tract, and red nucleus corresponds to the location of these structures on the MRI image (upper arrow, lower arrow and R, respectively). The location of STN is then apparent from the template. Inset demonstrates that STN is not visible on the MRI image.

Finally, despite small differences between the position of the left and right STN [11], comparison with the location of a contralateral electrode placed previously is helpful.

Each of these criteria is repeatedly used until a target is identified that best satisfies them all. The trajectory is then chosen using a probe-view feature to avoid the ventricles and sulci, making small adjustments of the entry point as necessary and using SPGR sequences because the sulci are exaggerated by inversion recovery sequences. Choosing the entry point on the dural surface rather than on skin or bone minimizes difficulties with operative angles during burhole construction.

Although the DBS trajectory typically passes through 4 to 6 mm of STN, the actual maximum diameter of the STN is 13 mm in its superoanterior–inferoposterior dimension [12]. Even though a longer length of STN does not necessarily confer clinical benefit [13,14], we attempt to make use of this anatomic fact by choosing our entry points as anteriorly as possible to maximize the length of the DBS electrode within the STN unless prohibited by the patient's hairline or by the sulcal anatomy.

We implant the left and right electrodes on separate days because we believe that simultaneous implantation can increase the risk of cognitive decline, and that the 'brain sag' during the first implantation can reduce stereotactic accuracy if a second implantation immediately follows. There are no Class I data supporting this belief, but it is consonant with our experience, discussed in the literature [15] and supported by the edema surrounding the DBS electrode [16]. An MRI is obtained for planning on the day of the second implantation. Because of concerns that the use of some MRI sequences could increase the risk of electrode heating or movement due to magnetic forces, we obtain only an axial inverse recovery sequence with limited SAR values. We have had no associated morbidity in 60 consecutive scans, and permanent neurological morbidity from such scans has not been reported [17] when the DBS system is implanted in a standard fashion and when using a standard head coil. We use MRI scans rather than CT sequences, believing that the superior display of anatomy conferred by MRI facilitates the process of pattern recognition needed for identification of the STN. This viewpoint is challenged by reports of excellent stereotactic precision obtained by fusing an operative CT with preoperative MRI data [18], but we nonetheless feel that the added MRI information helps to interpret this difficult and poorly visualized anatomy.

Table 2
Criteria for localization of thalamus (VIM).

3 T MRI sequences fused to operative 1.5 T sequences
Orient dataset to AC–PC plane
Use vertical axis of 3rd ventricle rather than interhemispheric plane for orientation
Use MRI slice just superior to AC–PC plane corresponding to Hd + 0.5 on Plate 53 of SWA[a]
Choose initial target 25% of AC–PC distance anterior to PC and 50% of AC–PC distance lateral to midline
Target should be adjacent to internal capsule
Use junction of mammillothalamic tract and Forel's H2 to guide placement ('H1 + H2' on slice Hd + 0.5 on Plate 53 of SWA[a])
Use of resident Schaltenbrand–Wahren atlas
Symmetry to contralateral side if prior electrode has been placed

[a] SWA = Schaltenbrand–Wahren atlas [8].

Thalamic target (VIM). Our approach for thalamic targets is similar to that for the STN, using the criteria in Table 2. After the images have been merged, a modified axial slice is chosen just superior to the AC–PC plane that contains the base of the targeted VIM nucleus. The anterior–posterior length of the third ventricle is measured, and an initial target chosen as the point lying 25% of this distance anterior to the posterior commissure and 50% of this distance from midline. The position of the target is then changed so that it is just medial to the internal capsule, visualized in either the inversion recovery or SPGR images. Because the medial portion of the signal thought to be internal capsule is more likely to be the thin reticular nucleus of the thalamus encasing the lateral aspect of the thalamus, the target will in fact lie within the adjacent VIM. The MMT is then identified where it blends into Forel's fields (see Table 2). The target site is then modified to lie on a line angled 45° to the horizontal through this junction, again adjacent to the internal capsule. This site corresponds to the base of the VIM (Fig. 2). Finally, the stereotactic atlas within the planning software is used in the same fashion as for STN targeting.

Pallidal target (GPi). Our approach to pallidal targets is similar (see Table 3). Our preferred target is the posteroinferior portion of the GPi, inferior enough to allow assessment of adjacency to the optic tract during intraoperative stimulation, but superior enough so that the upper and middle contacts of the electrodes will also reach the dorsal portions of the GPi. Small changes are made so that the target site lies on a line bisecting the cerebral peduncle [19]. The atlas within the planning software is used as before. Because the posterior portion of the GPi is narrow, 3-D reconstructions are useful in avoiding the very narrow posterior segment that would allow stimulation to spread to the adjacent internal capsule (Fig. 4). The probe view is used as before, and the trajectory is constructed to avoid the ventricle and sulci.

Table 3
Criteria for localization of globus pallidus (GPi).

3 T MRI sequences fused to operative 1.5 T sequences
Use of AC–PC plane
Use MRI slice 4 to 5 mm inferior to AC–PC plane corresponding to slice Hv-4.5 on Plate 55 of the SWA[a]
Choose posterior portion of GPi
Use 3D model to verify position
Use of resident Schaltenbrand–Wahren atlas
Symmetry to contralateral side if prior electrode has been placed

[a] SWA = Schaltenbrand–Wharen atlas [8].

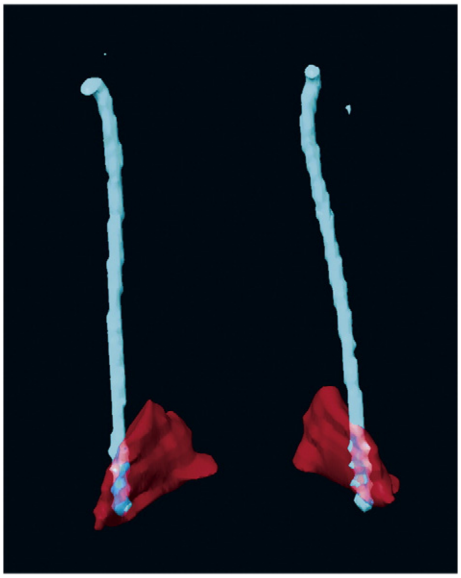

Fig. 4. 3D reconstruction from MRI images of left and right GPi viewed from their posterior aspect, merged with reconstruction of DBS electrodes from postoperative CT images merged with the MRI dataset. The DBS trajectories were chosen to traverse the posterior portion of the GPi while remaining anterior enough to avoid the narrowest portion of the GPi that would allow the stimulation to spread to the adjacent internal capsule.

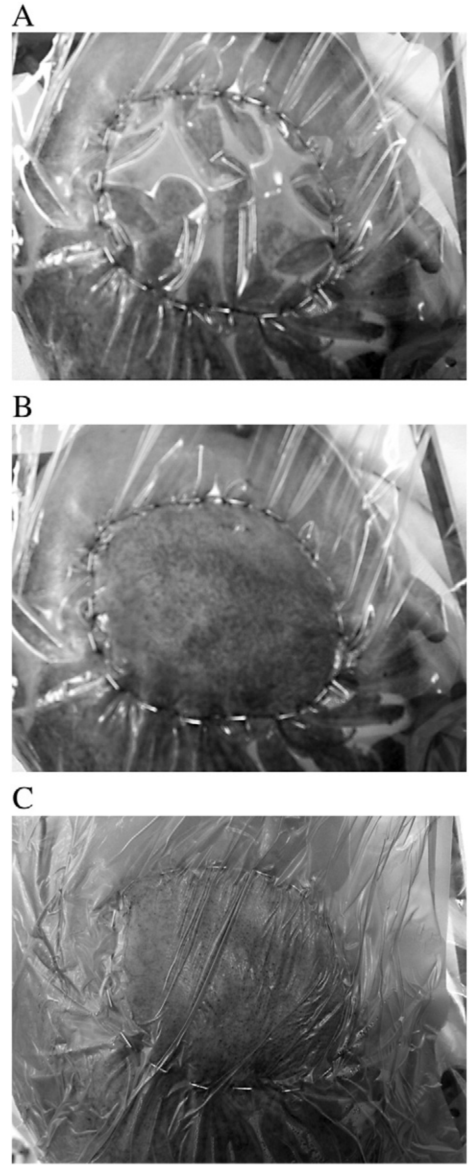

Fig. 5. (A) The clear drape is stapled to encompass the desired field after infiltration with local anesthetic. (B) The center of the drape is cut away. (C) The area is covered with an antimicrobial adhesive plastic layer to create a watertight barrier.

Draping

Nuance 2: draping

The importance of the interaction between the patient, surgeon and anesthesiologist in these awake procedures motivates our choice of operative draping. We cut three C-arm drapes along their folds to create rectangular, transparent sheets. After infiltrating the scalp with local anesthetic, the central piece is stapled to a circle surrounding the planned surgical incision (Fig. 5A). The plastic within the circle is then cut away (Fig. 5B), and a sheet of antimicrobial adhesive plastic layer (Ioban Antimicrobial Drape, 3M, St. Paul, Minnesota) is placed to cover the exposed skin and the layer of plastic overlying the staples (Fig. 5C). This creates a watertight seal between the surgical field and the remainder of the scalp. The ends of the drape are anchored to IV poles on the left and right of the patient, and the central portion of the drape is elevated and supported by a crossbar placed between the IV poles. One end of a second sheet is anchored to the left IV pole, and the other end is anchored to an IV pole placed towards the foot of the bed to create a clear wall around the left side of the patient; the third sheet is used to create an identical wall around the right side. The result is a tall, clear U-shaped wall surrounding the patient that creates spacious work areas for the surgeon and anesthesiologist, allows clear visualization from either side, and provides a watertight seal to the surgical field (Fig. 6). The anesthesiologist is in clear line of sight with the surgeon.

The use of clear drapes has several advantages. First, the surgeon can directly see and evaluate the responses of the patient to intraoperative stimulation and neurological testing. Second, the personnel operating the DBS stimulator during macrostimulation can directly see the surgeon, allowing communication by hand gestures (for example, holding up 2 fingers to indicate 2 volts) to obviate the effects of suggestion upon the patient's responses (see *Nuance Seven*). Third, efficient communication between the surgeon and anesthesiologist is enhanced. Fourth, the patient can see in all directions and is therefore less claustrophobic, calmer and more receptive to neurological testing. Finally, the plastic sheets are inexpensive (about $8 each) and their cost does not erode into the profit margins of the procedure (see *Nuance 6*).

Burhole issues

Nuance 3: burhole construction

We open both the burhole and the dura as widely as possible, exposing a relatively large area of cortex. Although this strategy takes time and allows egress of CSF, it confers several advantages. First, a wide cortical exposure allows direct visualization of the electrodes as they enter the brain, ensuring that the electrodes are not subtly deviated by contact with the surrounding pia, dura or bone and thus avoiding small deviations of the electrodes at the surface that can produce significant errors for deeply seated targets. Second, a wide exposure facilitates insertion of the electrodes without damage to surrounding veins, and allows a gentle retraction of the vein from the entry point with a nerve hook if necessary. Injury to these small veins

Fig. 6. Clear drapes used to create a U-shaped barrier between the anesthesiologist and the surgeon.

is not always innocuous, especially because the tissue they drain is not resected. Third, bleeding is more easily controlled, and gentle tamponade more effective, when the exposure is wide than if working through a small opening.

The burhole is created with a 14 mm perforator; burholes made with other drills will not accommodate the plastic annulus provided in the DBS kit used to anchor the electrode to the skull (see *Nuance Twelve*). The exposure is enlarged by removing the inner table at the depth of the burhole with a 2 mm Kerrison rongeur. A larger rongeur is not used in order to minimize any potential painful stretching of the dura, and a small amount of lidocaine can be injected into the dura through a bent 27 gauge tuberculin needle if manipulation of the dura is painful. Control of epidural bleeding with small bits of surgicel is more easily accomplished at this stage than after the dura has been opened, but the surgicel must be wedged well under the bone edge to allow visualization of the entire cortical exposure. The dura is then coagulated, opened in a cruciate fashion, and removed to the bony edge of the burhole. We have found that repeated coagulation alternating with the use of a 1 mm Kerrison ronguer is useful for this purpose, and that the small size of this Kerrison allows the dura to be cut rather than torn or pulled.

A wide exposure through the burhole carries the disadvantage of allowing CSF to escape, thus increasing the possibility of aggravating 'brain sag'. CSF leakage is minimized, but not eliminated, by plugging the burhole with gelfoam and tissue glue as soon as the initial guide tubes are placed (see *Nuance Four*).

Nuance 4: CSF leakage

Because stereotactic precision can be compromised by the escape of CSF from the burhole, many centers plug the hole with tissue glue as soon as the initial electrodes or guide tubes are placed. The glue also serves to blunt the normal cerebral pulsations, thus protecting the brain from impact throughout the case. However, the glue is tenacious and can be difficult to remove, especially if it seeps beneath the bone or dural edges. Furthermore, repeated tugging and suction upon the mass of glue can jar the electrode and guide tube, thereby increasing the risk of intracranial hemorrhage. One could choose to leave the glue in place, but we are reluctant to leave a foreign body that has been exposed during such a relatively long procedure.

To address these difficulties, we place a single layer of gelfoam within the burhole before the glue is applied, thus protecting the epidural and subdural spaces (Fig. 7). At the end of the case, a gentle pull on a corner of the gelfoam easily dislodges the mass of glue and allows its removal without excessive movement of the surrounding electrodes and tubes.

Nuance 5: anchoring the electrode with good cosmesis

Although several devices are available to anchor the electrode to the skull after implantation, we have chosen to use the apparatus supplied by the manufacturer in the DBS kit. The electrode is trapped between a stiff plastic annulus that fits snugly into the burhole and a silastic cap that fits onto the annulus. After the electrode has been placed, the tips of a curved hemostat are inserted into two holes in the annulus, decreasing its diameter slightly so that it can be inserted into the burhole where it springs back to its native shape to wedge tightly against the skull. The DBS electrode is pushed gently into a groove on the inner aspect of the annulus, and the silastic cap is then pushed into the annulus, thereby wedging the electrode firmly in place. There are a few minor nuances worth mentioning (the use of a Penfield 1 dissector to wedge the electrode into the groove, tilting the cap so that its flange inserts into a large groove in the annulus smoothly without dislodging the electrode, being aware that placement of the cap may drive the electrode unnecessarily further into the brain, placing some gelfoam into the burhole before final application of the cap) that do not merit a separate section.

Although this device effectively anchors the DBS electrode, it protrudes above the level of the outer table to create a noticeable bulge even when the wound is healed. These bulges can be distressing to some patients because they are easily palpated, and can be disfiguring in male patients with receding hairlines. In rare cases these bulges can threaten wound integrity.

Yamamoto addressed these problems by the process of counter-sinking, in which a circular annulus is drilled around the burhole to a depth of a few millimeters with the aid of a custom annular drill bit [20]. We have found it possible to achieve the same result with careful use of a more conventional small round cutting bur. Placing the annulus within the resulting trough and using the silastic cap as described above then serve to anchor the DBS electrode while keeping the top of the cap at the level of the outer table of the skull (Fig. 8). Care must be taken to ensure that the trough is drilled to a uniform depth in order to ensure that the annulus wedges properly within the burhole. Despite best efforts, and especially when the skull is thin, the annulus may not wedge and must be held in place by miniplates.

A different approach to this problem is to use one of the burhole covers provided by other manufacturers. A disadvantage of these is their cost, discussed in *Nuance Twelve*.

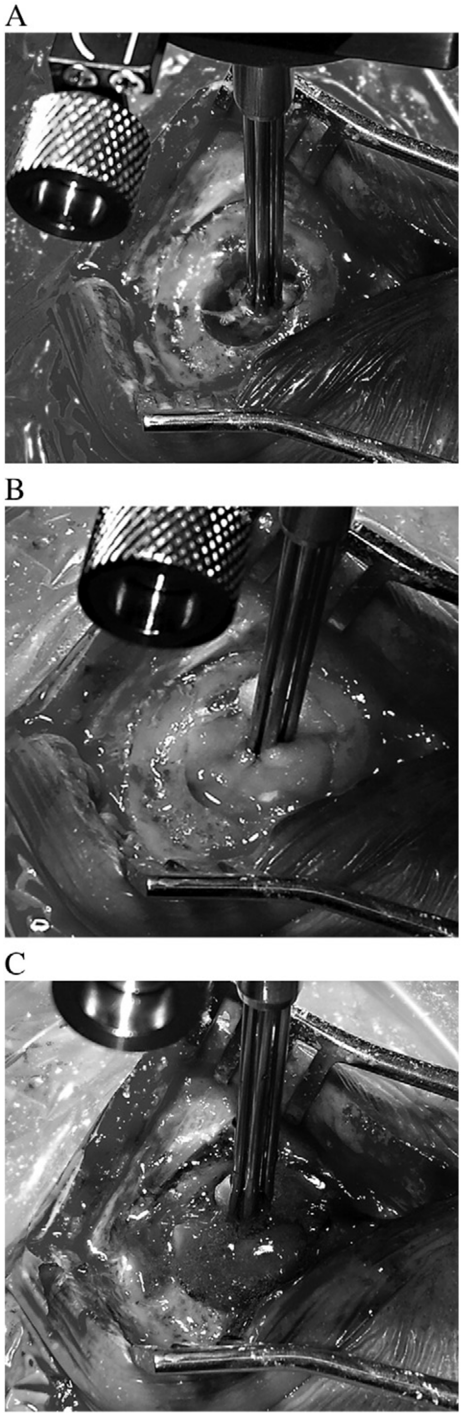

Fig. 7. (A) Burhole with guide tubes placed. (B) Gelfoam placed in burhole. (C) Tissue glue placed over burhole and gelfoam.

Physiological testing

Nuance 6: management of microelectrode data

Visualization of microelectrode recording (MER) data is difficult for several reasons. First, the data are not continuous, but instead consist of a series of discrete encounters with neurons or background changes along the course of the stereotactic tract. Recordings must therefore include a complex array of recording depths and signal descriptions. Second, the data are voluminous, often arising from measurements taken every half-millimeter along several 2.5 cm tracks. For these reasons, the data are not easily displayed on a single computer screen in a way that allows comparison of the data from the various tracts, and yet this is precisely what is needed to detect the subtle boundaries of stereotactic targets.

Our approach to these difficulties is as follows. We typically interrogate 3 to 5 tracks simultaneously, beginning at a location 2.5 cm above our calculated target. For the initial 1.5 cm, the tract is largely within the internal capsule, and so data are obtained every 1 mm as the electrodes are slowly inserted under motorized control. As is common in many centers, the electrodes are held stationary for approximately 1 min at each data acquisition to allow the brain tissue to equilibrate. The remainder 1 cm of the tract traverses more critical structures, and so data are acquired every 0.5 mm.

For each measurement, data are entered into a chart containing a separate column for each track and a separate row for each distance above or below the target. Three items are recorded. First, a subjective impression of the background signal is made, graded on a scale from 0 to 3. This amounts to grading the thickness of the horizontal strip that appears across each recorded signal. The second recorded item is a subjective assessment of cellularity, graded on a scale from A to C. The third item is a representative screenshot taken of all tracks each time data are collected.

Although these ratings of amplitude and cellularity are subjective and qualitative, they can be helpful when searching for changes that might indicate entrance or exit into the targeted structures. Review of the screenshots is less subjective and usually provides a more definitive indication of signal change.

The screenshot data, however, are voluminous and difficult to adequately view on a single computer screen. We therefore print the snapshots and tape them to the operating room wall, arranging the pages so that each column of data represents a single track aligned according to depth (Fig. 9). This simple method of display allows efficient and direct comparison of the different tracks, enables detection of subtle changes in background and cellularity, facilitates simultaneous review by several people, and enhances the discussion of interpretation and decisions. A minor but useful nuance is to assign the same printing color to each track during each case to facilitate review.

Nuance 7: responses to macrostimulation

Observation of the responses of the patient to simulation during implantation depends on the cooperation and interpretation of the patient, and can be unreliable if the patient is aware of the stimulation magnitudes. To minimize the effects of suggestion, the surgeon stands behind the patient and gives instructions to change the voltages with hand signals that the patient cannot see. Frequency and pulse duration are held constant (usually at 180 Hz and 60 ms, respectively), and voltages are restricted to whole numbers (0, 1, 2, etc.). The process is facilitated by the use of clear drapes (see *Nuance Two*), and allows a rapid assessment of the effects of stimulation without the confounding influence of suggestion.

Electrode anchoring

Nuance 8: backup marks on the electrode

The DBS electrode is held in a cradle-like device as it is inserted through the stereotactic frame to its target, and then carefully removed from the frame and anchored to the skull after confirmation of location. If the electrode is inadvertently dislodged during this process, it may be necessary to remove it entirely and reinsert to the target. However, if a marking pen is used to mark the electrode in reference to a fixed landmark on the cradle device, the electrode can be repositioned without removal by inserting the exposed end back into the cradle so that the mark is again at the landmark.

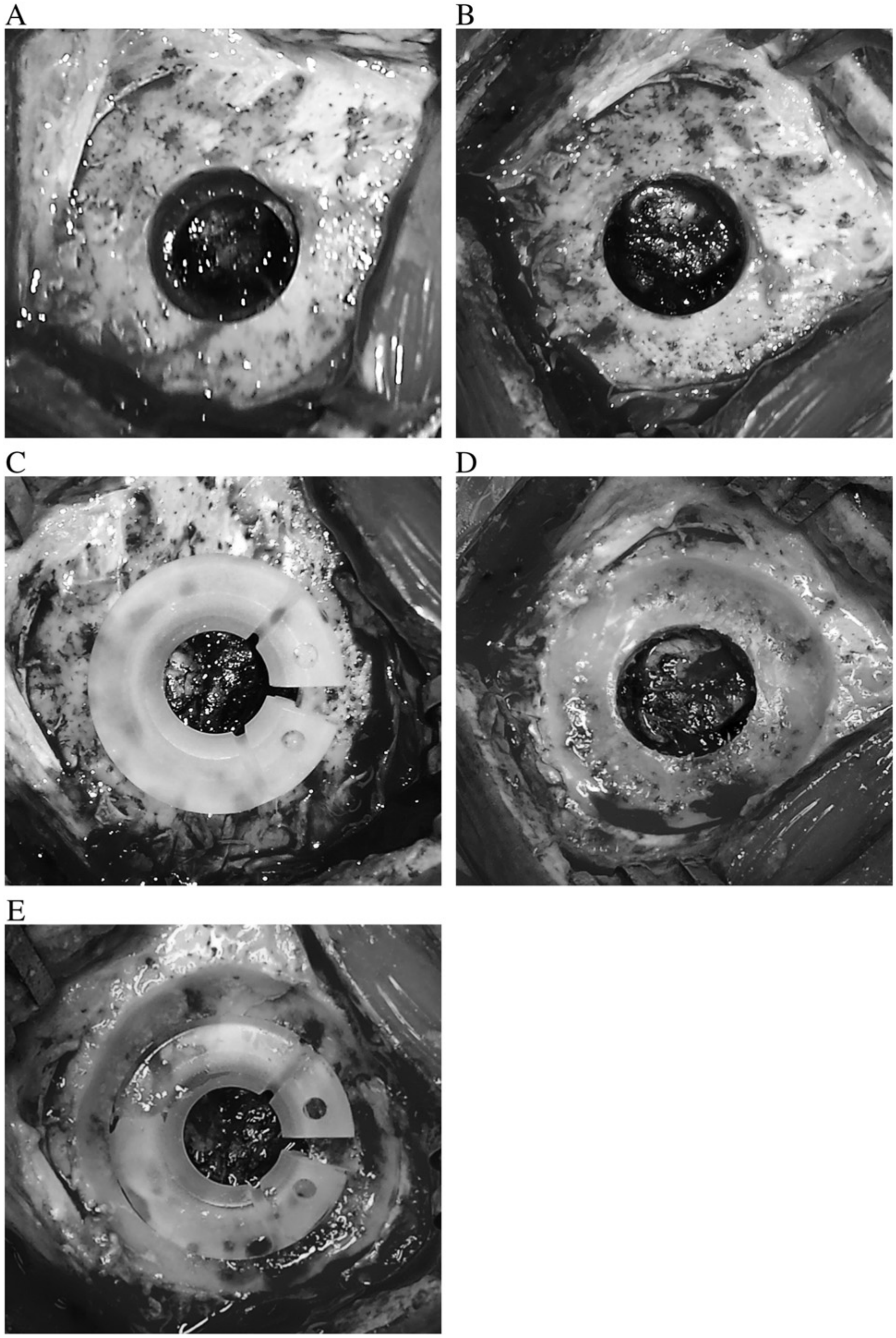

Fig. 8. (A) Burhole. (B) Burhole with inner table removed. (C) Plastic ring in burhole. Note protrusion above skin edge. (D) Annulus drilled around burhole. (E) Plastic ring within annulus. Note countersinking below skin edge.

Nuance 9: fluoroscopic marking

We and other centers use fluoroscopy to verify that the electrode tip remains at its target while the electrode is removed from the frame and attached to the skull. A standard method is to arrange the fluoroscope so that cross hairs on two reticles are superimposed on the electrode tip, attaching the electrode to the skull, and then checking again to ensure that the tip remains aligned with the crosshairs. We have found, however, that precise alignment of the fluoroscope with the reticles can be difficult and time consuming, and so we address the problem in a different fashion. The fluoroscope is first positioned to obtain a lateral projection, placing the x-ray source as close to the head as possible to enhance magnification of the electrode tip and then choosing an appropriate magnification setting. A marking pen is then used to trace the position of the electrode and the outline of the frame on the fluoroscope screen (Fig. 10). The electrode is then removed from the frame and attached to the skull, taking care to avoid movement of the fluoroscope. If the subsequent x-ray image shows that the frame and DBS electrode remain

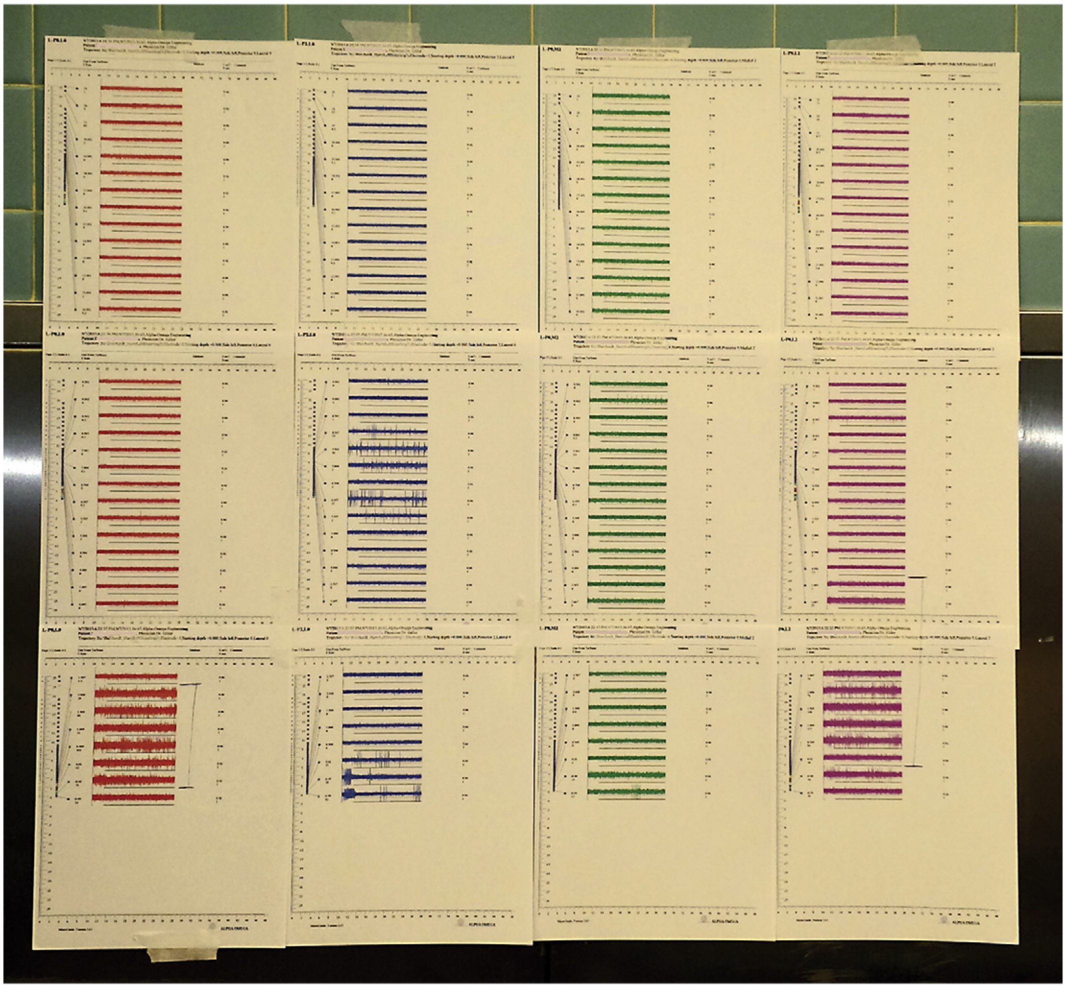

Fig. 9. Printed output of microelectrode tracks taped to operating room wall. Each column and color represent a single track, and tracings of the same depth are placed at aligned level.

superimposed on the markings, the position is accepted; if the frame remains superimposed on its markings but the electrode does not, then the electrode is moved until it again aligns with its markings; if neither the frame nor electrode remains superimposed on their markings (usually because the fluoroscope has moved relative to the head), the DBS electrode is moved an amount that matches the distance of the frame outline from its markings. Although this method requires that frame movements relative to the fluoroscope be estimated when they occur, we have found it effective and quick in practice.

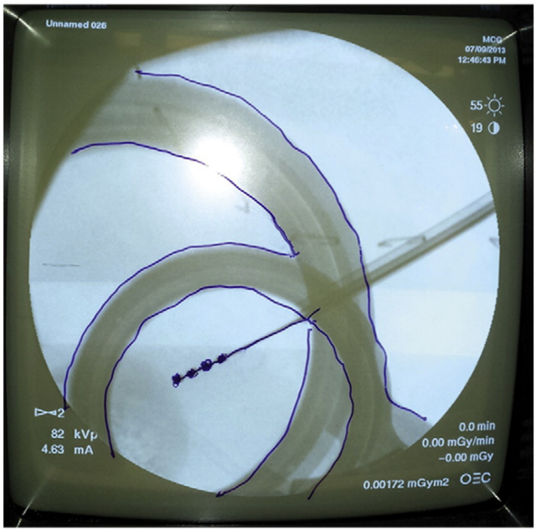

Fig. 10. Outlines of DBS electrode and stereotactic frame traced on fluoroscopic display screen.

Nuance 10: protection of the electrode tip

Many centers will subcutaneously tunnel the free end of the DBS electrode to a point posterior and superior to the ear, making a separate incision to expose this end at a later date to attach it to the lead connecting it to the DBS generator. The manufacturer supplies a protective cap that is anchored to the electrode by 4 set screws, and a silastic sleeve fitting over the cap that is anchored by two sutures. A minor nuance is that the set screws should be only gently tightened to avoid damage to the delicate electrode. For centers such as ours that implant the left and right electrodes on different days and use MRI during the second implantation, it is important to note that MRI artifact arising from the metal in the protective cap can confound stereotactic planning [21]. Accordingly, we protect the first electrode with the cap supplied by the manufacturer, removing its single metal connector with a hemostat. The electrode is placed within the cap and the entire assembly covered with the silastic sleeve provided by the manufacturer, which is anchored with two 00 silk sutures. This provides adequate protection to the electrode, and the rigidity of the tip facilitates the tunneling process more efficiently than if a simple silastic sleeve is used as we described previously [21].

Nuance 11: tunneling

The annulus provided by the manufacturer fits into the burhole and contains two small grooves into which the DBS electrode can be wedged to hold the electrode in position. Although an intuitive choice would be to place the groove in the line of direction of the tunneling so that the electrode does not kink, we have found it more useful to position the groove away from the direction of tunneling so that the electrode is held away from the site of dissection, thus decreasing the risk of inadvertent electrode removal. We have also found that dissecting between the galea and pericranium is more efficient than the use of other planes. Care should be taken to avoid penetrating the galea during this dissection, because the risk of injury to the electrode during subsequent dissection increases if its tip lies in the subcutaneous tissue rather than deep to the protective galea.

Financial considerations

Nuance 12: preserving the profits of DBS surgery

Although it may seem odd to consider finances in a discussion of operative nuances, such concerns are vital to the integrity of a DBS program. Most patients receiving DBS in the United States are funded by Medicare or Medicaid, with a reimbursement that is predetermined and fixed. The cost of additional equipment such as drapes or burhole covers (see *Nuance Two* and *Nuance Five*) cannot therefore be passed to the patient or to the insurance agencies, and must instead be paid from the profits earned by the hospital.

An approximate calculation demonstrates the importance of these concerns. Assuming a reimbursement level of $34,000 for a single sided DBS, a cost of electrode and generator of $12,000, and indirect costs of $5,000, the hospital will gain a profit of $17,000. If special drapes and burhole covers are purchased for a combined cost of $2,000 the profit decreases by 12%.

This degree of decrease in profit may seem small, but it can profoundly affect the finances of the hospital component of a neurosurgical practice. For example, neurosurgeons performing one implantation each month will have to perform an additional two cases annually to compensate for a 12% fall in profit, and those performing two implantations each month will have to perform more than three extra procedures each year. This is equivalent to the hospital donating two or three extra operating days annually without payment *simply to pay for the added expenses of special drapes and burhole covers*. Furthermore, changes in hospital profits can be detrimental to the neurosurgeon even if professional fees are not affected. For example, the physician's institution often weighs the financial success of the physician's efforts within the hospital when determining salary and promotion, penalizing the surgeon if hospital operative margins are low. Moreover, surgical programs failing to produce a financial profit risk being rationed or even cancelled, especially within a difficult economic environment. Furthermore, most viable business entities realize that even small decreases in profit margins can have significant adverse effects, and will not willingly accept these decreases. There is little reason to feel otherwise for DBS programs.

In the rare occasions in which miniplates are required to anchor the burhole ring, profits remain preserved because the miniplates are inexpensive (about $45 each) compared with more complete burhole covers. A more difficult issue arises from the recent availability of new, more expensive DBS generators. It is not likely that every patient will benefit from these new devices, but it is certain that their cost cannot be passed to the insurance carrier and that hospital revenues will fall whenever they are implanted. Subsequent neurosurgical decisions that weigh the benefits to the patient against the viability of the DBS program will be both difficult and uncomfortable. In any case, operative decisions that affect the finances of a DBS effort deserve consideration as important operative nuances.

Overall technique

Nuance 13: gentle touch

The admonition that tissue should be delicately handled need not be reiterated to neurosurgeons, but is surprisingly important for DBS implantation. Slight impacts to the stereotactic frame or to the guide tubes that produce only small displacements of the electrodes at the skin surface can produce large shear movements of the tissues several centimeters below because of magnification by the length of the associated lever arm. Furthermore, many such impacts may increase the risk of small hemorrhages in the subcortical structures and thereby increase the risk of significant neurologic deficit. Despite the lack of Class I evidence, we therefore use a slow, deliberate 'feather light' touch throughout the implantation.

Nuance 14: single operator

The large number of steps required for DBS implantation is due in part to the intricate connections needed for microelectrode recording and stereotactic placement of the electrode. Each of these steps offers ample opportunity for an unwanted dislodgement of the DBS electrode. To minimize such errors, a single operator performs all steps of the implantation, assisted by others only for the task at hand and only under direct vision; each movement is executed singly, one at a time. As for *Nuance 13*, we believe that doing so minimizes complications despite the lack of Class I evidence for its support.

Discussion

Every complex operative procedure contains steps that seem to be minor, yet are essential for success. The aggregate of such steps constitutes the craft of surgery, and different choices are naturally made by different surgeons and institutions. Assessment of these nuances with scientific studies, however, can be difficult enough to be prohibitive. For example, our suggestion to simply tape the microelectrode data to the wall may improve operative decisions by facilitating group discussions in the operating room and by clearly displaying an enormous amount of data in a succinct fashion that cannot be obtained using a single computer screen. Testing this hypothesis, however, would require a way to assess the operative discussions, a way to classify the various decisions, and a way to relate these considerations to patient outcomes or radiographic findings. Given the difficulty in making and validating these assessments, as well as the heterogeneity of procedures and patients, it is doubtful whether such a study would ever be attempted. Nevertheless, a discussion of this nuance can be helpful not only because some may find it of value, but also because such a discussion draws attention to the problem of data display even to those who do not favor taping the data to the wall.

For these reasons, we present and classify the aggregate of minor nuances that we have found helpful during DBS implantation. We do not believe that these are the only ways to address the operative problems inherent to this procedure, nor do we claim that they are superior to other methods. Indeed, our comments are likely to provoke disagreement, criticism and controversy on virtually every point, especially because there is little Class I evidence to support any aspect of DBS implantation [1]. Our hope is that a presentation of our particular choices may be of value to those facing the same operative issues by suggesting certain solutions and by drawing attention to particular problems.

We found it helpful to classify the nuances into 7 categories: stereotactic planning, draping, burhole issues, physiological testing, electrode anchoring, financial considerations, and overall technique. To our knowledge, majority of the nuances we report have not been extensively discussed, although many may already be in use in other institutions. These include the suggestion to plan in a 'round-robin' fashion; the use of the axis of the third ventricle rather than the interhemispheric fissure for image alignment; the use of Forel's fields as landmarks for STN and VIM targeting; choice of STN location on the sagittal images; the use of the probe view for targeting; the use of the 'warp' feature in Adobe Photoshop to merge the atlas with the MRI images; consideration of the advantages of an anterior burhole; the use of 3D imaging in choosing a GPi target; the construction of a clear wall of drapes and the use of hand signals for DBS adjustments; the creation of a watertight barrier using clear drapes; countersinking the burhole with a standard drill bit; the use of a gelfoam layer beneath tissue glue covering the burhole; recognition of the impact of operative decisions on the finances of the DBS program; the use of printed sheets to efficiently review the voluminous data from microelectrode recording; the use of backup marks on the electrode and the fluoroscopic screen in anticipation of unwanted electrode movement; and an awareness that operative movements tolerated during other procedures can produce motion at the tip of the deeply placed electrode that can be harmful. Nuances that have been reported previously but were included for completeness include the use of the mamillothalamic tract for planning [9], the use of sagittal images [10], the suggestion to countersink the burhole [20] (although we observe that this can be done without need for a custom drill bit), and the need to use non-metallic electrode caps if the implantations are staged [21].

We implant the left and right electrodes on different days when targeting the STN or GPi, believing that simultaneous implantation can increase the risks of cognitive decline. Although this issue has been addressed by others [15] and is supported by MRI findings [16], there is no Class I evidence to support either a staged or simultaneous implantation. Some of the nuances presented here do not therefore apply to centers implanting both sides in a single procedure.

Although we believe that microelectrode recording is a useful tool to confirm location, we do not map the somatotopy of targets such as the STN because of the lack of Class I evidence supporting this approach, the length of time operative time needed for its execution, and our personal experience that good clinical results can be achieved without meticulous mapping of kinesthetic neurons. Again, it is not our purpose to address the well-argued controversy surrounding the use of MER, but rather, to discuss some selected operative nuances that have been helpful in our institution.

Conclusion

We identify and classify a collection of modest technical suggestions that we have found helpful in overcoming operative problems arising during DBS implantation. Variations of some of these techniques are likely to be already used by other institutions, but most have not been extensively described. Individually taken, these points may seem trivial and obvious. But details matter in neurosurgery, and it is our hope that this collection of operative nuances may be of use to those facing the thorny problems arising in DBS implantation.

Conflict of Interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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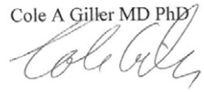

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